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Analyzing data from a PDV microphone

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Photon Doppler Velocimetry (PDV) is used at Los Alamos National Laboratory to measure extremely fast velocities (on the order of 0.01 - 5 km/s) of projectiles during material testing procedures. This kind of testing is extremely important to understand how materials behave in extreme conditions (such as in nuclear explosions). PDV data is created by summing an incident beam with a Doppler shifted reflection, forming a beat frequency. The beat frequency is directly proportional to the velocity of the reflecting surface. We explored a new way of using PDV: measuring slow velocities (less than 1 m/s). The principle method we used was to measure vibrations in a Mylar sheet due to incident sound waves. I analyzed these files using both my own coding as well as a program designed at NSTec for this purpose. Analysis included performing Fourier Transforms, extracting velocity as a function of time, and playing the velocity function through a speaker to recreate the initial sound. We were able to create a successful microphone, though playback quality was poor. The limiting factor was the low velocity of the Mylar sheet, which was about 0.2 m/s. Other methods are now being explored to extract velocity data in a more efficient manner. During this project I gained extensive experience in programming, data analysis, problem solving, and communication. I learned that one must be creative in order to solve complex problems, approaching them from various angles. I also gained a lot of practice working on a team, which consisted of a high school student, another college intern, and our mentor.

Analyzing data from a PDV microphone

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Photon Doppler Velocimetry (PDV) is used to measure very fast velocities (on the scale of 0.01 - 5 km/s). We applied this technology to a new application, measuring miniscule vibrations of Mylar in response to a sound wave. PDV data is created by summing an unshifted laser beam with a Doppler-shifted reflection, forming a beat frequency. We analyzed the PDV measurements of the beat frequency to determine the velocity of the Mylar sheet. Several steps are used to accomplish this, including Fourier analysis. Finally, the velocity data is converted into a sound file and played back, attempting to replicate the initial sound. The efficacy of this particular PDV microphone was limited due to the small velocities of the Mylar, but further applications will be explored.

I. WORKINGS OF PDV AND PROJECT DESIGN

PDV makes use of the Doppler shift observed when a beam of light is reflected off a moving surface. When the incident beam and the Doppler-shifted beam are summed, a beat frequency is obtained. For velocities much smaller than the speed of light, we have[1]:

$$f_{beat} = \frac{2v}{\lambda} \tag{1.1}$$

Here v is the velocity of the reflecting surface, λ is the wavelength of light, and f_{beat} is the resulting beat frequency. Our PDV system uses infrared light at 1550 nm. If this light is reflected off a surface moving at v = 1 m/s, then equation (1.1) gives:

$$f_{beat} = \frac{2 \times 1 \text{ m/s}}{1550 \text{ nm}} = 1.29 \text{ MHz} \tag{1.2}$$

Because f_{beat} and v are directly proportional, we obtain the conversion factor of $\frac{1 \text{ m/s}}{1.29 \text{ MHz}}$, which allows us to easily transition between beat frequency and surface velocity.

A PDV microphone was made by taping a sheet of Mylar across the end of a cylindrical housing. The housing has one hole opposite from the Mylar where a fiber optic probe is inserted. This probe emits the collimated, unshifted laser beam at 1550 nm and also collects the Doppler-shifted reflection, transmitting it back to the detector. In the PDV detector box, the Doppler-shifted light is mixed with some of the unshifted light directly from the laser, giving a beat frequency that is proportional to the velocity of the Mylar. Figure 1 shows a schematic of the microphone, and photos of the

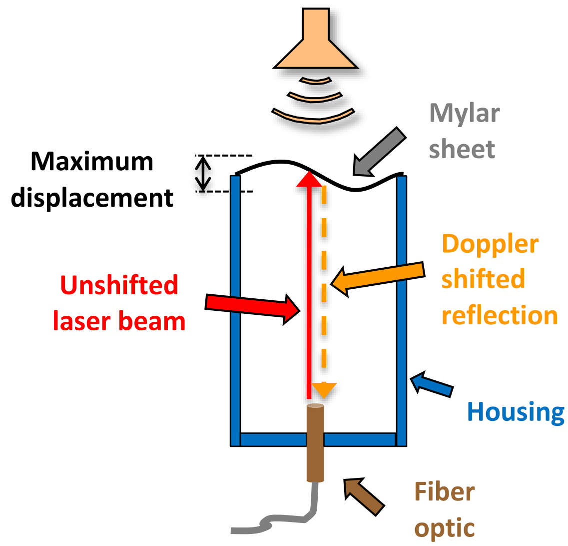

FIG. 1. Schematic of microphone design. Collimated laser light is emitted from a fiber optic probe and reflects off a moving Mylar sheet. The reflected light is gathered by the same probe and transmitted back to the PDV electronics box, where it is mixed with some of the unshifted laser light.

FIG. 2. Actual PDV microphones. Two basic microphone designs were used, both pictured here.

actual microphones can be seen in Figure 2. We used two main microphone designs of differing dimensions to compare their response. We also varied the conditions of the experiment by adjusting the Mylar properties: taut, loose, with holes, without holes. However, the specific results from these tests are not addressed in this paper.

II. EXAMPLE DATA

To illustrate how PDV data is collected and analyzed, a detailed example is provided. Suppose we begin by playing a 1.0 Hz sound wave into the PDV microphone. This will cause the Mylar to oscillate with a period of 1.0 sec, as seen in (A) of Fig. 3. The laser hitting the Mylar sheet will be Doppler-shifted in proportion to the Mylar velocity. When summed with the incident beam, a beat frequency will be created, as shown in (B) of Fig. 3. At times 0, 0.5, and 1.0 seconds, both the Mylar speed and the beat frequency of the PDV data are at a maximum. At times 0.25 and 0.75 seconds, the Mylar is stationary; thus the frequency of the PDV data at those points is instantaneously 0 Hz. (C) of Fig. 3 shows that once the velocity is extracted from the data, the velocity is both rectified and phase shifted by $\pi/2$ compared to the original displacement function. A more detailed explanation of the velocity extraction follows.

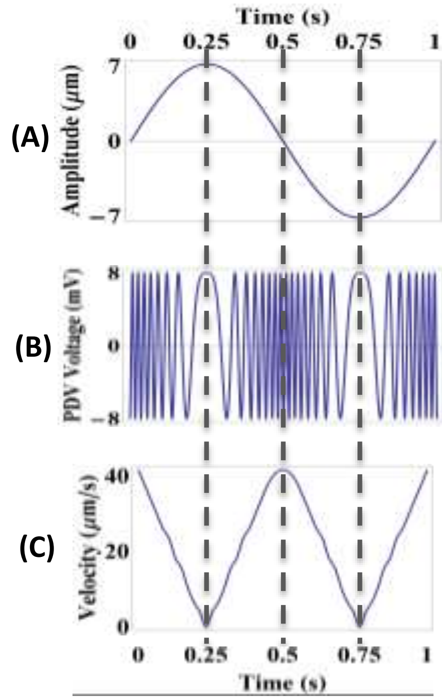

FIG. 3. (A) Mylar displacement from a 1.0 Hz sine wave. (B) Example PDV data, with frequency proportional to Mylar velocity. (C) Rectified velocity function extracted from (B).

III. ANALYZING THE DATA

In order to extract the frequency information (and thus velocity) from raw PDV data, it is necessary to perform a Discrete Fourier Transform (DFT). However, because the Mylar velocity is oscillating so quickly, this Transform must be applied many times over the data series in small chunks, or windows. We used windows ranging between 1024 and 65536 points, depending on the sampling rate of the oscilloscope. After the DFT is performed, a velocity spectrum is generated and assigned to the time value of the middle of the window. The window is then shifted further along the data series, and the DFT is performed again. These windows overlap one another, with a step size to window size ratio of 1:8. This analysis technique can be seen in Fig. 4, where the top picture is raw PDV data and the bottom picture is a plot of velocity spectra as a function of time. Each 1-pixel-wide column represents a spectrum generated from the DFT of one window.

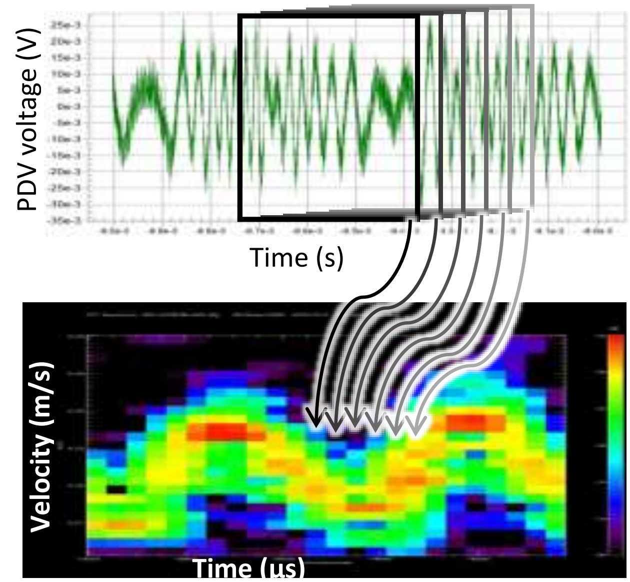

FIG. 4. Analysis of PDV data. Discrete Fourier Transforms (DFTs) are done on windows of data, providing velocity spectra as a function of time. The window is shifted and the DFT done repeatedly.

After the DFT analysis is complete, the velocity spectrum for each step can be used to identify the most prevalent velocity for that step in time. When extracted, this produces a velocity function over the time interval of interest. Such a velocity function can be played through a speaker in an attempt to recreate the initial tone. We substitute the velocity for the position in our approximated audio output because the two are periodic and related by a phase shift.

The type of PDV we used only returns the absolute value of the velocity, not distinguishing between positive and negative motion. This causes all the resulting velocity functions to be rectified functions. If a sine wave has a frequency of 100 Hz, its rectified wave will have a frequency of 200 Hz. In pitch, doubling the frequency corresponds to raising the tone an octave higher. Thus all of our velocity playback files were an octave too high, creating the need to de-rectify them. This proved to be problematic. Some of the velocity functions showed very clean and clear oscillations, allowing for an algorithm to change the sign of the function after each crossing of the x-axis, as shown in (A) of Fig. 5. However, some of our trials returned velocity functions that included many imperfections, such as frequent jumps to 0 m/s. Used on these velocity functions, the same de-rectifying algorithm destroyed the original waveform, as shown in (B) of Fig. 5.

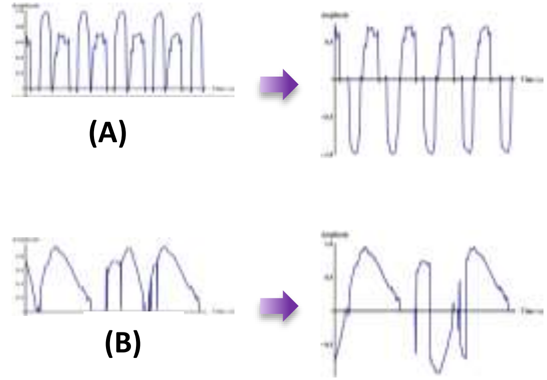

FIG. 5. (A) An originally clean waveform de-rectified with accuracy. (B) The waveform displays irregularities, and the same de-rectifying algorithm destroys the initial waveform.

IV. LIMITATIONS OF THE FOURIER ANALYSIS

PDV is normally used for measuring very fast velocities, on the order of 0.01 - 5 km/s. In all of the data we collected, the maxiumum Mylar velocity we found was 0.2 m/s. A maximum velocity this low put us at a large disadvantage when analyzing the data. For a DFT, the maximum freqency detectable is based on the time between samples. We obtain the following relationship[2]:

$$v_{\max} = \frac{1}{2\Delta t} \times \frac{1 \text{ m/s}}{1.29 \text{ MHz}}, \qquad (3.1)$$

where Δt is the time between samples. To take about 5 data points per cycle of PDV data, we needed to sample at a rate of about 1.5 kHz to detect a velocity of 0.2 m/s. While it was possible to increase the sampling rate drammatically, this did not help with the low Mylar velocities. We needed a small velocity resolution, which is dependent on the window length (T_{window}) of the DFT[2]:

$$\Delta v = \frac{1}{T_{window}} \times \frac{1\text{ m/s}}{1.29\text{ MHz}} \tag{3.2}$$

In order to see small changes in velocity, it is thus necessary to include as many data points as possible in the window when taking the DFT. However, including too many points will average frequencies over a large fraction of the sine wave (created by the sound), thus reducing the resolution in time. If the DFT is done over too small a section of data, attempting to enhance some interesting feature, the velocity resolution is compromised. This would not be such a problem if the velocities of the Mylar sheet were bigger. It would then not be necessary to have such a large time period in the Transform window because a fine velocity resolution would not be needed.

V. FUTURE WORK

Taking this application of PDV further, we want to map the evolution of tone on a saxophone. Because of the tapered shape of a saxophone, it is logical to assume that at different positions along the tube there are different resonant frequencies. An accoustical microphone cannot pick up resonance on a certain portion of the instrument; it will pick up the sound from the entire horn. If we could accurately measure these small velocities at various points on the saxophone, however, it would be possible to use PDV to map out how the tone changes as it flows through the horn. This could provide information on how to better manufacture saxophones, as well as maximizing resonance while playing.

FIG. 6. Future work includes using the PDV microphone to map the evolution of tone as it progresses through a saxophone.

Unfortunately, we expect the velocities found in the brass body of a saxophone to be even smaller than those we observed in the Mylar sheet. By extending a sliver of Mylar from one part of the saxophone, we could amplify the local vibrations to make them within the detection limit of PDV. Such a modification could allow for detailed resolution of waveforms on the saxophone, but needs to be tested for functionality. If another way to extract frequency from small-velocity PDV data is found, that could also help solve this problem. Finally, using a frequency offset PDV would allow us to distinguish between positive and negative velocities, both eliminating the need for de-rectification and doubling the observed velocity amplitude.

VI. CONCLUSION

PDV is a well established tool for determining velocities of fast-moving projectiles, but its use to measure small velocities was previously unexplored. We were able to create a successful PDV microphone, although the playback files were often distorted and introduced a lot of background noise. The difficulty in recreating the sound was mainly due to small velocities that oscillated quickly, producing limitations in velocity resolution from our Fourier analysis. If vibrations could somehow be amplified, PDV would perform much better at reproducing sound.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

1. Jewett Serway, *Physics for Scientists and Engineers with Modern Physics*, Vol. III, 7th edition.
2. B. Campbell and J. Peatross, *Experimental Methods in Physics*, Brigham Young University, Provo, UT, 2011, p. 83.